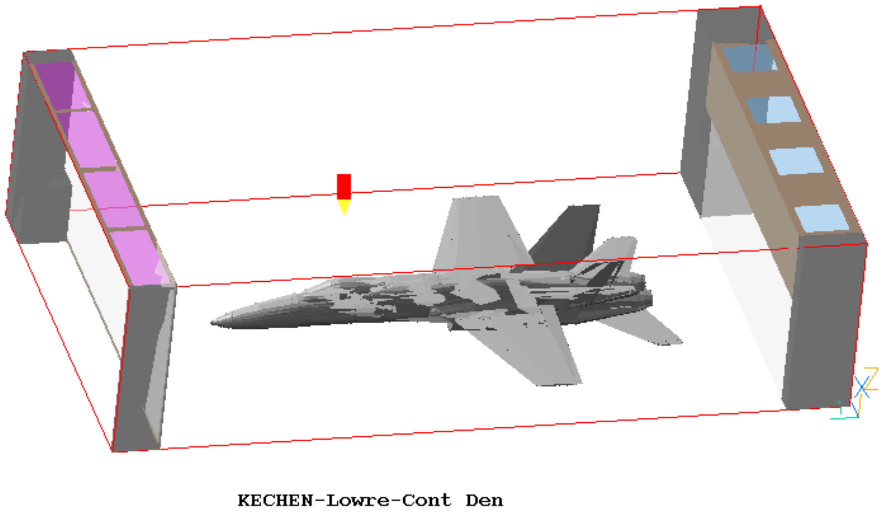
# CFD Modeling & Verification in an Aircraft Paint Hangar




Airflow Rates and OSH&E Protection

*E2S2 May 9-12, 2011*

# Report Documentation Page

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**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

# Navy and NIOSH Collaboration

- **Navy Bureau of Medicine and Surgery (BUMED), IH Division**
  - **Assists CNO with health and safety of Navy aircraft artisans**
  - **Quarterly monitoring for hexavalent chromium and hexamethylene diisocyanate**
  - **Sharing data and ideas, based on IH expertise and knowledge of day-to-day operations**
- **National Institute for Occupational Safety and Health (NIOSH)**
  - **Application of computational fluid dynamics to ventilation design**
  - **Tracer gas studies to evaluate ventilation effectiveness**
  - **Project final report (still in draft)**

# Short History of Efforts

- **1985 – Started writing Department of Navy (DON) design manual:**
  - **Concern: excessive energy use in hangars when supplied air respirator systems are *required* due to Cr(VI) and isocyanate exposure**
- **1997 – Interpretation Letter: DON to OSHA on Paint Hangar Flow**
  - *http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=22383*
  - Even after DON-OSHA correspondence, whether corrosion-control hangars are **spray areas** or **spray booths** still requires **clarification**
  - *But must comply with* 29 CFR 1910 Subpart Z (AKA the PELS)

- **2005 – Began a Navy environmental RDT&E project to model aircraft paint hangars**

# Energy Issues

- **Once through vs. recirculation**
- **Airflow across the hangar vs. immediately around aircraft**

# Safety and Health Issues

- **Safety: Flow must dilute to below 25% of the LFL for combustible & flammable materials**
  - Velocity of 20 fpm meets requirement
  - Today's material is less flammable than materials used when the OSHA standard was first promulgated

- **Health: Workers cannot go w/o respirators**
  - Cr(VI)
  - Isocyanates
  - Exposure problem ***INSIDE*** aircraft and some obstructed areas (e.g. wheel wells)

# Environmental Issues

- **Typically focus on Delta P across filtration & hangar +/- Pressure**

# Health Effects and Evaluation Criteria

- **Hexamethylene Diisocyanate**
  - **Respiratory sensitization and occupational asthma (can be fatal)**
  - **Once sensitized, a worker must never be exposed again, even to trace amounts (essentially ends their ability to work in that environment)**
  - **NIOSH Ceiling 0.140 mg/m$^3$ (10 min.); NIOSH REL 0.035 mg/m$^3$; ACGIH TLV TWA 0.035 mg/m$^3$**
- **Hexavalent Chromium**
  - **NIOSH potential occupational carcinogen (lung and upper airway)**
    - REL 1 $\mu$g Cr(VI)/m$^3$ ACGIH TLV 10 $\mu$g Cr(VI)/m$^3$
  - **OSHA PEL of 5 $\mu$g Cr(VI)/m$^3$ for 8-hr TWA**
    - Special provision for aerospace industry: when workers are painting aircraft or large aircraft parts the employer must use feasible engineering and work practice controls to reduce worker Cr(VI) exposures to levels $\leq 25$ µg/m$^3$. The employer must supplement its engineering and work practice controls with respiratory protection to achieve the PEL. *Applicable to work done in corrosion-control hangars?*
- **Explosion Hazard (easily controlled)**
  - **Lowest LEL among coating mixture components is 0.9% or 9,000 ppm. Concentrations are < 1% of LEL. NFPA requires < 25% of LFL.**

# Hexavalent Chromium Exposures

- Aircraft Priming 2008 – 2010
  - 18 % of hexavalent chromium samples > 5X PEL
  - Painters / Assistant Painters (hosemen)
  - Range 1.6 - 55.1 µg/m³
  - Mean 16.2
  - Median 11.7
- Highlighted dates indicate NIOSH study
- Exposures are for unbalanced, full flow
  - Supply = 136 fpm
  - Exhaust = 99 fpm

| Date | Location | Job Task | Monitoring Duration (minutes) | Concentration for the Monitoring Period ( µg/m³) | Work shift 8-hour TWA Results ( µg/m³) | Over-exposure (Yes/No) |
|---|---|---|---|---|---|---|
| 8 Jan 10 | Bay 8 | Priming E-2C | 293 | 8.1 µg/m³ | 4.9 µg/m³ | **Yes** |
| 8 Jan 10 | Bay 8 | Priming E-2C | 292 | 1.5 µg/m³ | 0. 18 µg/m³ | No |
| 13 Apr 10 | Bay 6 | Priming F/A-18 | 30 | 281.0 µg/m³ | 17.6 µg/m³ | **Yes 3.5x PEL** |
| 13 Apr 10 | Bay 6 | Priming F/A-18 | 27 | 183.0 µg/m³ | 10.3 µg/m³ | **Yes 2x PEL** |
| 13 Apr 10 | Bay 6 | Priming F/A-18 | 30 | 623.0 µg/m³ | 38.9 µg/m³ | **Yes 8x PEL** |
| 13 Apr 10 | Bay 6 | Priming F/A-18 | 33 | 654.0 µg/m³ | 44.3 µg/m³ | **Yes 9x PEL** |
| 17 Jun 10 | Bay 7/8 | Priming E-2C | 69 | 106.0 µg/m³ | 15.2 µg/m³ | **Yes 3x PEL** |
| 17 Jun 10 | Bay 7/8 | Priming E-2C | 72 | 65.9 µg/m³ | 9.9 µg/m³ | **Yes 2x PEL** |
| 17 Jun 10 | Bay 7/8 | Priming E-2C | 69 | 34.2 µg/m³ | 4.9 µg/m³ | **Yes** |
| 17 Jun 10 | Bay 7/8 | Priming E-2C | 69 | 97.3 µg/m³ | 14.0 µg/m³ | **Yes 3x PEL** |
| 23 Sep 10 | Bay 7/8 | Priming E-2C | 147 | 71.5 µg/m³ | 21.9 µg/m³ | **Yes 4x PEL** |
| 23 Sep 10 | Bay 7/8 | Priming E-2C | 479 | 25.2 µg/m³ | 25.1 µg/m³ | **Yes 5x PEL** |
| 27 Oct 10 | Bay 6 | Priming F/A-18 | 86 | 0.288 µg/m³ | 0.051 µg/m³ | No |
| 27 Oct 10 | Bay 6 | Priming F/A-18 | 85 | 8.37 µg/m³ | 1.48 µg/m³ | No |
| 23 Nov 10 | Bay 6 | Priming F/A-18 | 39 | 101.3 µg/m³ | 8.23 | **Yes 2x PEL** |
| 23 Nov 10 | Bay 6 | Priming F/A-18 | 38 | < 0. 66 µg/m³ | < 0.05 | No |
| 23 Nov 10 | Bay 6 | Priming F/A-18 | 39 | 215.3 µg/m³ | 17.49 | **Yes 3x PEL** |
| 23 Nov 10 | Bay 6 | Priming F/A-18 | 41 | 0.67 µg/m³ | 0.06 | No |
| 1 Dec 10 | Bay 5 | Priming F/A-18C | 87 | 119.0 | 21.6 | **Yes 4x PEL** |
| 1 Dec 10 | Bay 5 | Priming F/A-18C | 87 | 172.9 | 31.4 | **Yes 6x PEL** |
| 1 Dec 10 | Bay 5 | Priming F/A-18C | 73 | 0.43 | 0.6 | No |

# Hexavalent Chromium Exposures, cont.

## During Aircraft Priming 2008 – 2010

- 18 days of sampling
- 50 personal air samples
- 72% of samples above OSHA PEL, 5 μg/m³
- 16% of samples above OSHA aircraft industry limit, 25 μg/m³

| Date | Location | Job Task | Monitoring Duration (minutes) | Concentration for the Monitoring Period ( μg/m³) | Work shift 8-hour TWA Results ( μg/m³) | Over-exposure (Yes/No) |
|---|---|---|---|---|---|---|
| 9 Apr 08 | Bay 4 | Priming F/A-18 | 57 | 91.2 μg/m³ | 10.86 μg/m³ | **Yes 2x PEL** |
| 9 Apr 08 | Bay 4 | Priming F/A-18 | 57 | 149.9 μg/m³ | 17.80 μg/m³ | **Yes 3.5x PEL** |
| 9 Apr 08 | Bay 4 | Priming F/A-18 | 65 | 76.1 μg/m³ | 10.3 μg/m³ | **Yes 2x PEL** |
| 8 Jul 08 | Bay 3 | Priming F/A-18 | 325 | 26.9 μg/m³ | 18.2 μg/m³ | **Yes 3.5x PEL** |
| 8 Jul 08 | Bay 3 | Priming F/A-18 | 325 | 9.0 μg/m³ | 6.1 μg/m³ | **Yes** |
| 8 Jul 08 | Bay 3 | Priming F/A-18 | 325 | 13.9 μg/m³ | 9.4 μg/m³ | **Yes 2x PEL** |
| 8 Oct 08 | Bay 3 | Priming E-2C | 248 | 7.19 μg/m³ | 3.7 μg/m³ | No |
| 8 Oct 08 | Bay 3 | Priming E-2C | 252 | 24.9 μg/m³ | 13.1 μg/m³ | **Yes 2.6x PEL** |
| 8 Oct 08 | Bay 3 | Priming E-2C | 226 | 5.33 μg/m³ | 2.5 μg/m³ | No |
| 31 Mar 09 | Bay 1 | Priming Parts | 164 | 37.3 μg/m³ | 12.7 μg/m³ | **Yes 2.5x PEL** |
| 31 Mar 09 | Bay 1 | Priming Parts | 154 | 5.0 μg/m³ | 1.6 μg/m³ | No |
| 13 Jul 09 | Bay 12 | Priming UH-1 | 133 | 91.0 μg/m³ | 25.2 μg/m³ | **Yes 5x PEL** |
| 13 Jul 09 | Bay 12 | Priming UH-1 | 131 | 20.1 μg/m³ | 5.5 μg/m³ | **Yes** |
| 23 Jul 09 | Bay 6 | Priming F/A-18 | 39 | 36.7 μg/m³ | 2.98 μg/m³ | No |
| 23 Jul 09 | Bay 6 | Priming F/A-18 | 51 | 72.6 μg/m³ | 7.71 μg/m³ | **Yes** |
| 23 Jul 09 | Bay 6 | Priming F/A-18 | 49 | 540.0 μg/m³ | 55.12 μg/m³ | **Yes 11x PEL** |
| 23 Jul 09 | Bay 6 | Priming F/A-18 | 47 | 220.0 μg/m³ | 21.54 μg/m³ | **Yes 4x PEL** |
| 4 Aug 09 | Bay 6 | Priming F/A-18 | 27 | 166.0 μg/m³ | 9.3 μg/m³ | **Yes 2x PEL** |
| 4 Aug 09 | Bay 6 | Priming F/A-18 | 29 | 130.0 μg/m³ | 7.8 μg/m³ | **Yes 1.5x PEL** |
| 4 Aug 09 | Bay 6 | Priming F/A-18 | 29 | 578.0 μg/m³ | 34.9 μg/m³ | **Yes 7x PEL** |
| 4 Aug 09 | Bay 6 | Priming F/A-18 | 33 | 615.0 μg/m³ | 42.3 μg/m³ | **Yes 8x PEL** |
| 11 Aug 09 | Bay 2 | Priming parts | 102 | 11.8 μg/m³ | 2.5 μg/m³ | No |
| 11 Aug 09 | Bay 2 | Priming parts | 84 | 9.14 μg/m³ | 1.6 μg/m³ | No |

# Problem Statement

- **DON currently designs large paint facilities without the benefit of clear airflow criteria for large paint facilities**
  - **Initial design meetings, EACH design team spends considerable time rehashing the required airflow for large paint hangars**
  - **Without scientific documentation to prove lower flow is equally protective, Navy OSH staff requires design flow rate – 100 fpm, based on the OSHA ventilation standard, 29 CFR 1910.94, Table G-10, *Minimum Maintained Velocities Into Spray Booths.***
  - **Current recommended guidelines (ACGIH IV Manual) and standards (NFPA 33 & ANSI Z9.4) permit flow to 50 fpm for large facilities and 25% of the lower flammable limit, respectively.**

- **Each hangar industrial ventilation system designed to meet OSHA Standard 1910.94**
  - **$250k for capital costs (fan air, ductwork, pollution control systems)**
  - **Another $250k annually in energy & operating costs for EACH facility.**

# CFD Analysis Looks Easy… Yeah, Right!

- Finding the right modeling program
- Getting a “water tight” aircraft model.
- Finding the processing power
- Determining complexity levels
- Handling paint particulates and vapors

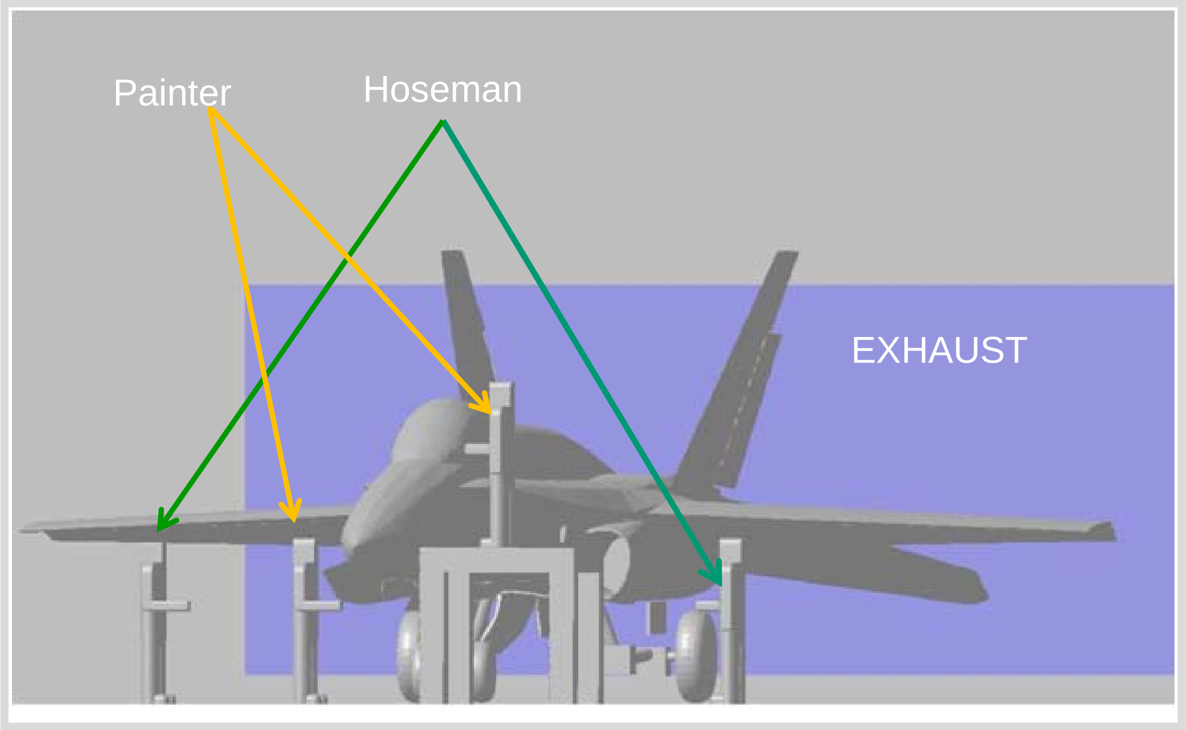
# Verification Pitfalls

- Artisans change process in the weeks between baseline and verification
  - Added a fabric blanket in front of filter to save filter bank blocking exhaust airflow during sanding

- Learn how to go w/o sleep
  - Consider working after hours to stay out of production's way
  - Observe what artisans are supposed to do & ACTUAL practices

- Expect maintenance surprises
  - Try figuring out the system Delta P w/ hole in exhaust plenum wall
  - Tracer gas MIRANs take a while to set up – back to sleep issue

# October 2010 Findings




Geometry of workers, exhaust wall filter, and F-18.

Hosemen farther from aircraft & further downwind than painters.

Contaminant source is located at the end of the painters' right arms.

**Houston - We have a problem!**

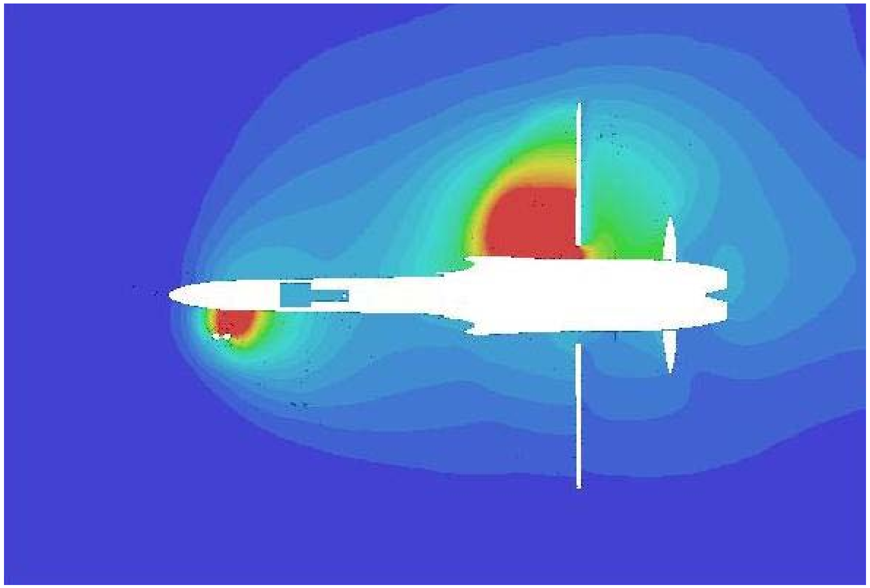
- **Supply 136 fpm**
- **Exhaust 99 fpm**

**CFD Analysis**

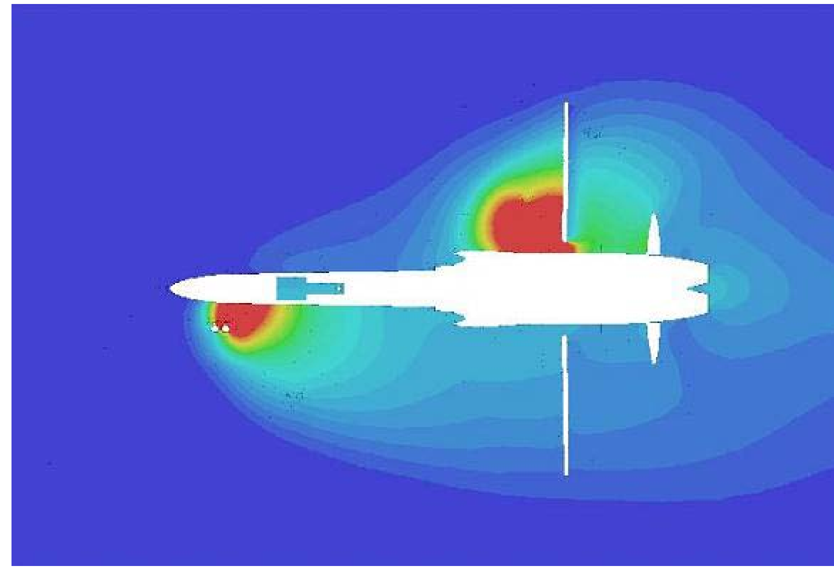
**=> Indicated turbulent flow near sources/workers**

**=> Identified improved OELs w/ balanced airflow**

# CFD Contours of MIBK Conc at BZ Height



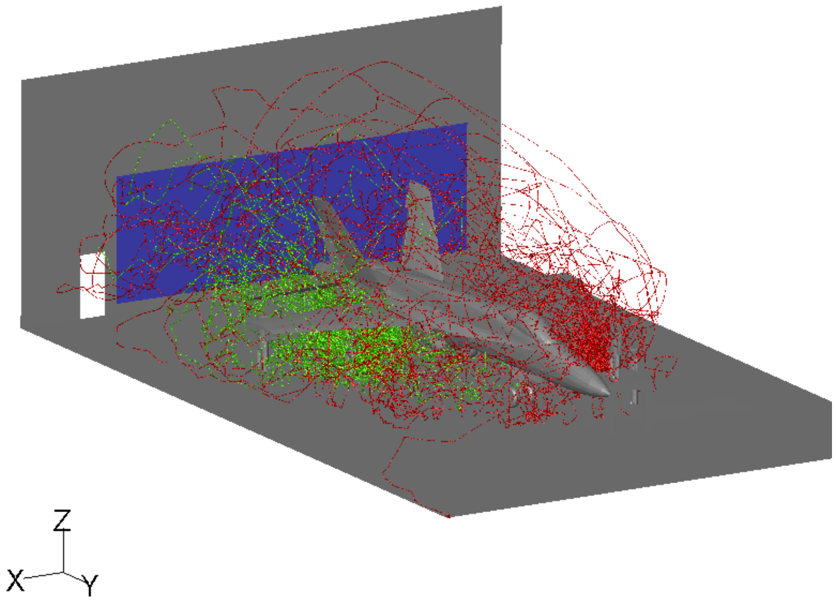
**Unbalanced Case**
125 fpm Supply & 75 fpm Exhaust



**Balanced Case**
75 fpm Supply & 75 fpm Exhaust

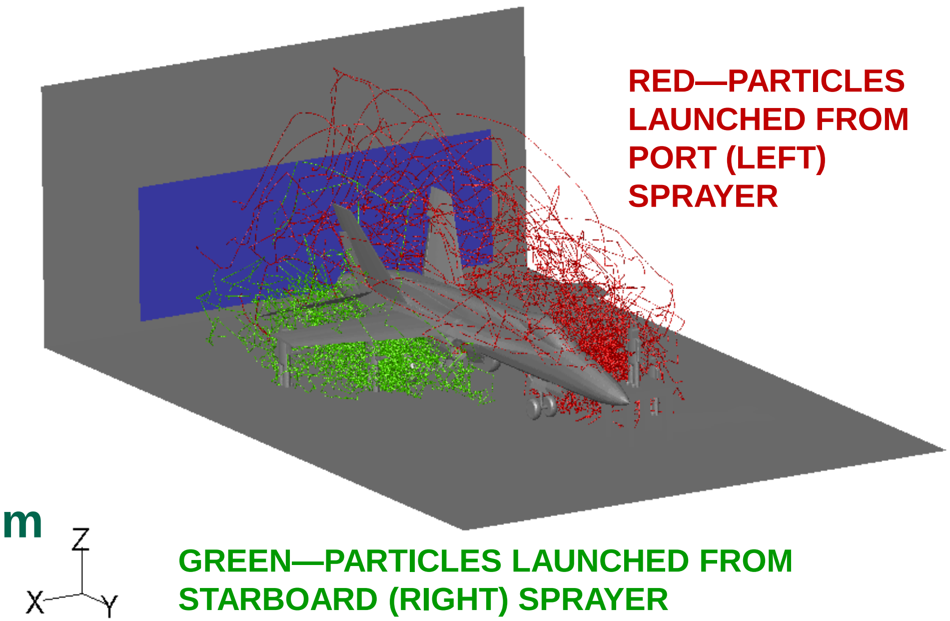
*High concentration areas and contaminant cloud are larger for the unbalanced case*

# Particle Tracks for Unbalanced Vs. Balanced Case




The balanced case shows less particle dispersion.

**Upper Left – 125 fpm supply & 75 fpm exhaust**



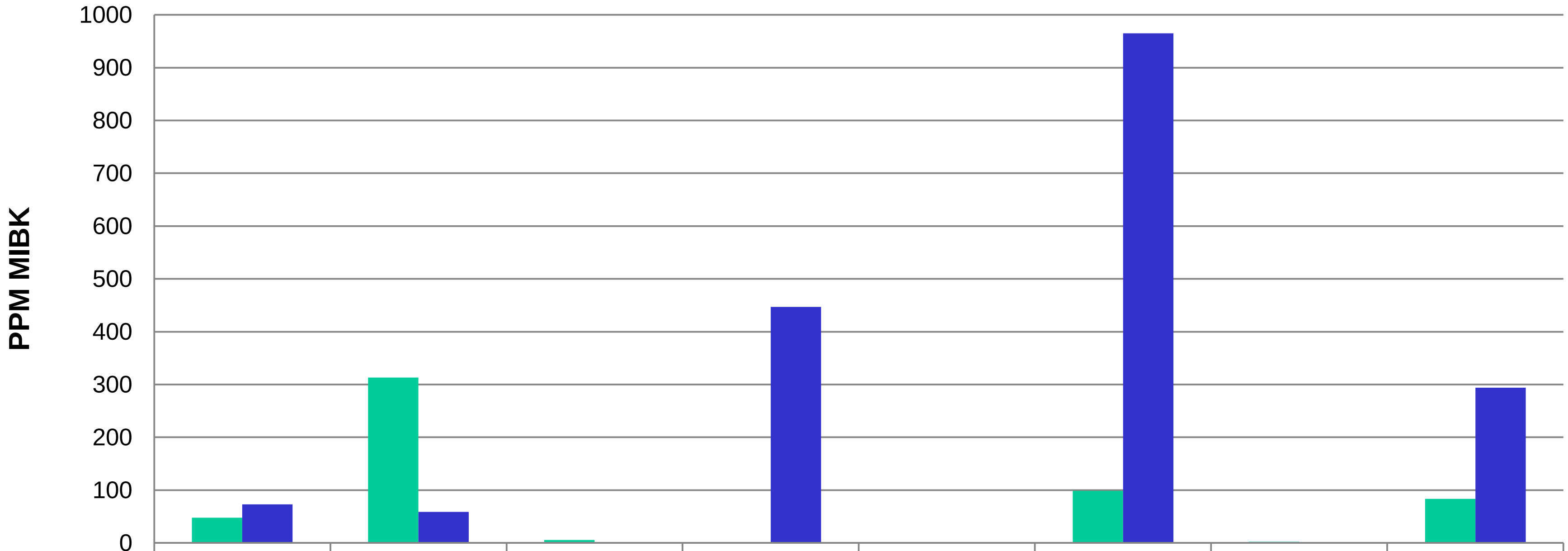

RED—PARTICLES LAUNCHED FROM PORT (LEFT) SPRAYER

**Lower Right – Balanced 75 fpm**

GREEN—PARTICLES LAUNCHED FROM STARBOARD (RIGHT) SPRAYER

# April 2010 Verification

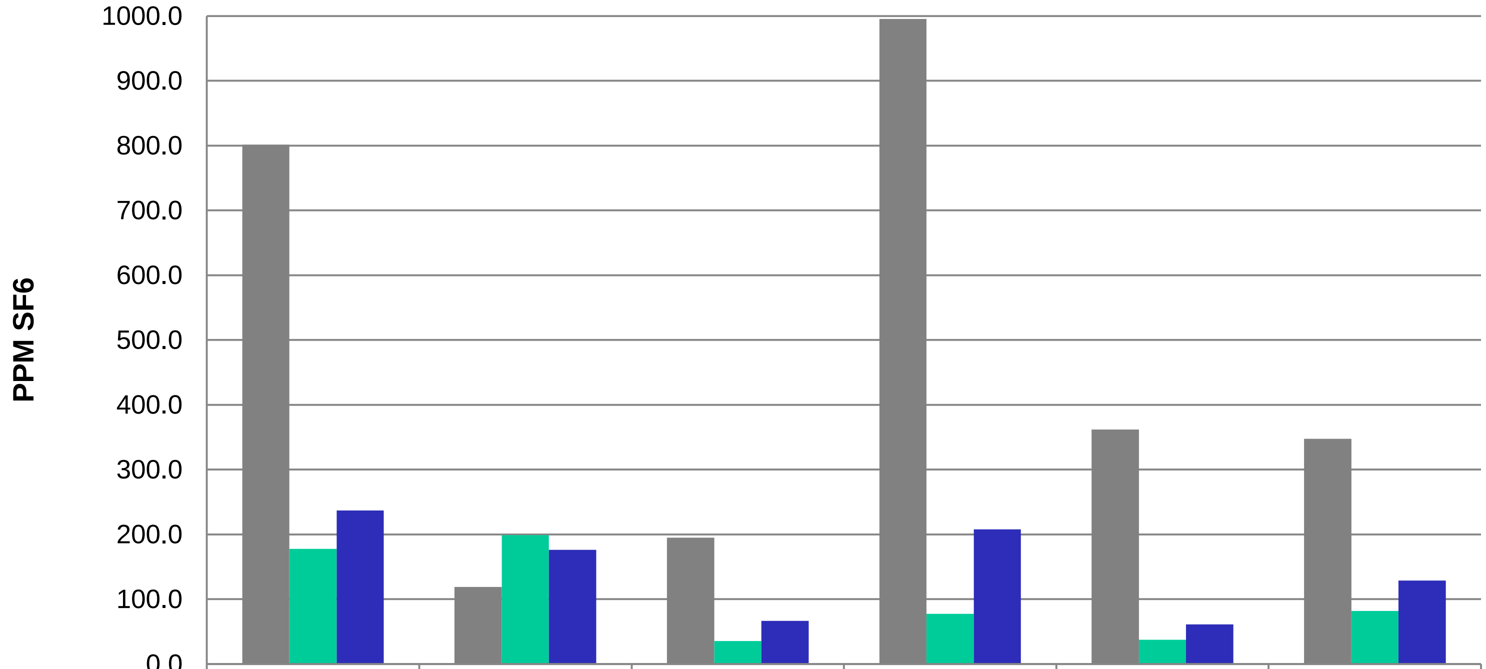
# CFD Modeled Conc. vs. Air Velocity & Location (run II)




| | BZ Height | Under Plane | Hoseman Port | Hoseman Starboard | Sprayer Port (scaffold) | Sprayer Starboard (wing) | Geometric Mean | Arithmetic Mean |
|---|---|---|---|---|---|---|---|---|
| 75 FPM | 47.9 | 313 | 5.85 | 0.59 | 0.00 | 98.6 | 2.07 | 83.61 |
| 100 FPM | 73.2 | 58.7 | 0.00 | 447 | 0.00 | 965 | 0.00 | 294.14 |

***CFD simulation results, at balanced flow velocities of 75 & 100 fpm, using an advanced turbulence model & stricter convergence criterion ($10^{-4}$)***

# Real Tracer ($SF_6$) Conc. vs. Air Velocity & Location (instrument ID)




| | Under Plane | Under Starboard Wing | Starboard Rudder (scaffold) | Port Side of Canopy (scaffold) | Under Port Wing | Geometric Mean |
|---|---|---|---|---|---|---|
| HALF-FLOW | 801.6 | 118.7 | 195.1 | 995.5 | 361.9 | 347.4 |
| 3/4-FLOW | 177.5 | 198.8 | 35.7 | 77.3 | 37.6 | 81.8 |
| FULL-FLOW | 236.9 | 176.3 | 66.6 | 207.7 | 61.2 | 128.7 |

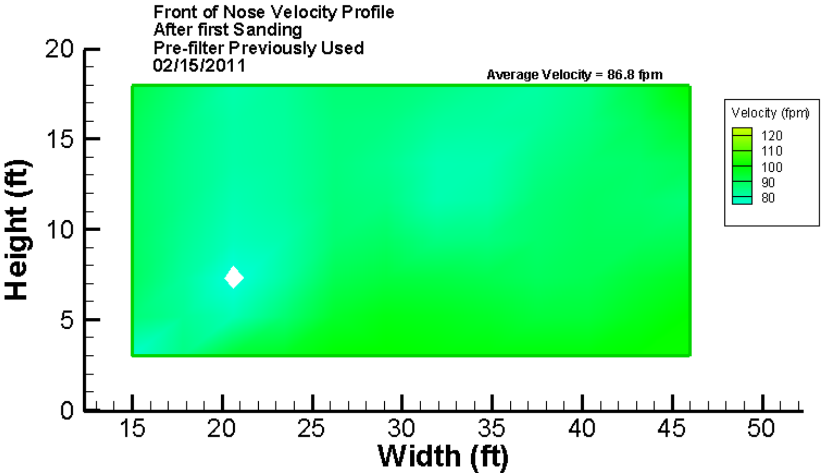
- ***Half, 3/4, and full flows correspond to unbalanced supply/exhaust velocity pairs of 73/49, 102/69, and 136/99 fpm, respectively***
- ***Tracer studies under balanced flows are underway***

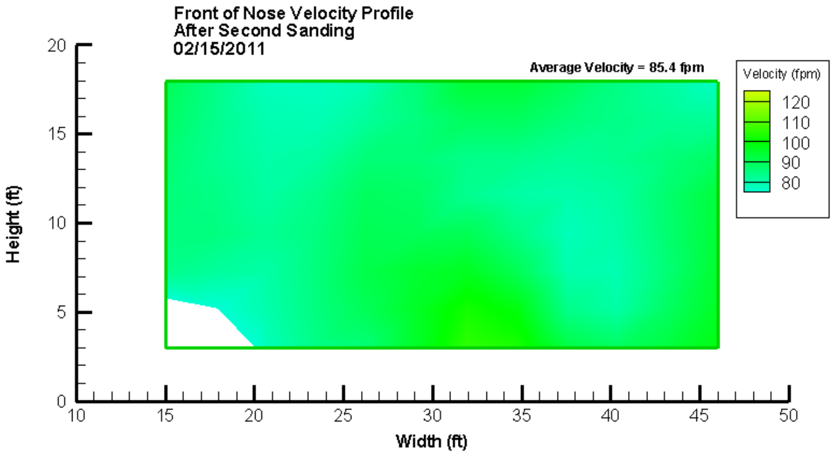
# October 2010 Painting Operations

***Hoseman is often downwind of sprayer (source)***

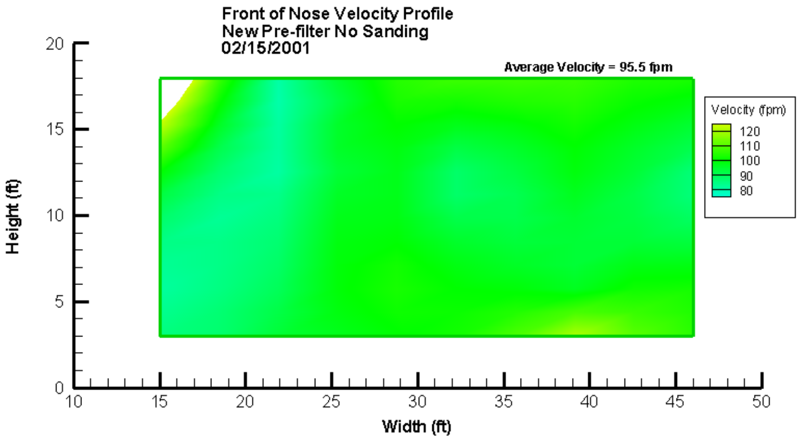
# UPSTREAM OF AIRCRAFT NOSE

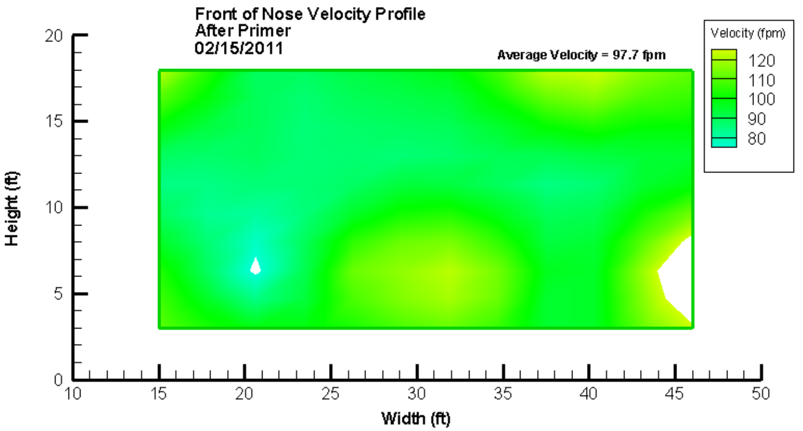
## ~ 8 to10 FT FROM SUPPLY WALL FILTER



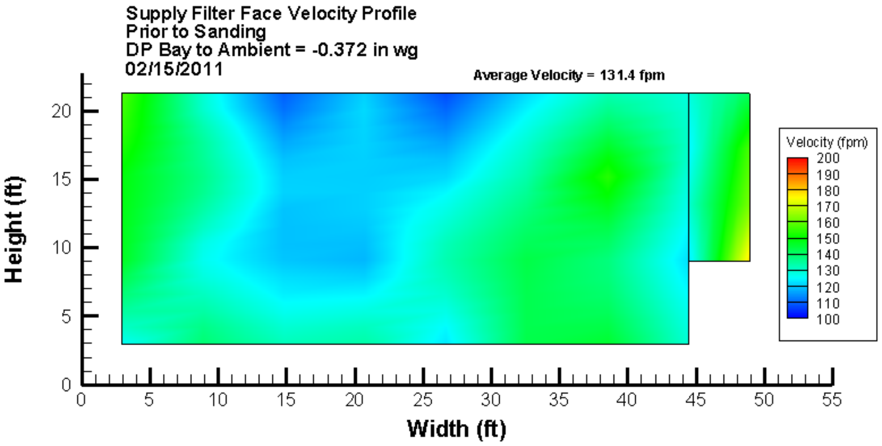



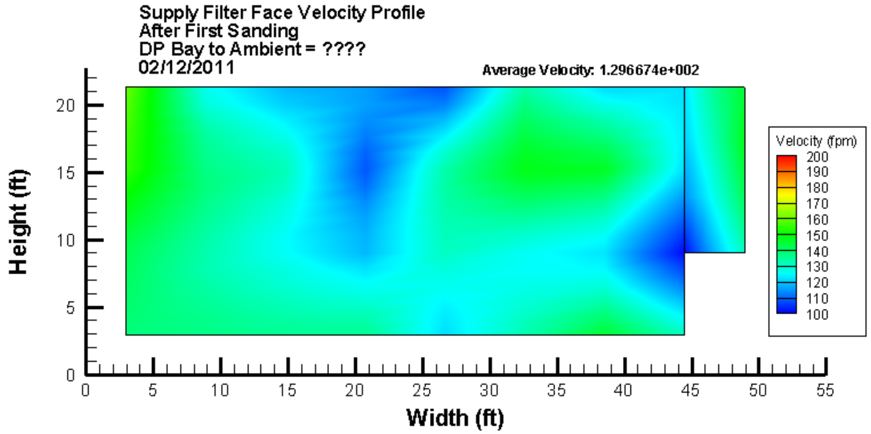

**Showing only the OSHA Range of 75-125 fpm. White color is outside the range.**

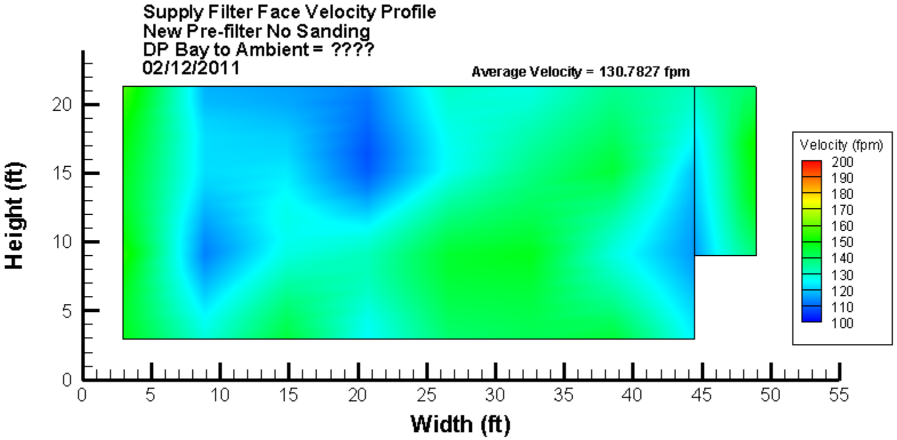


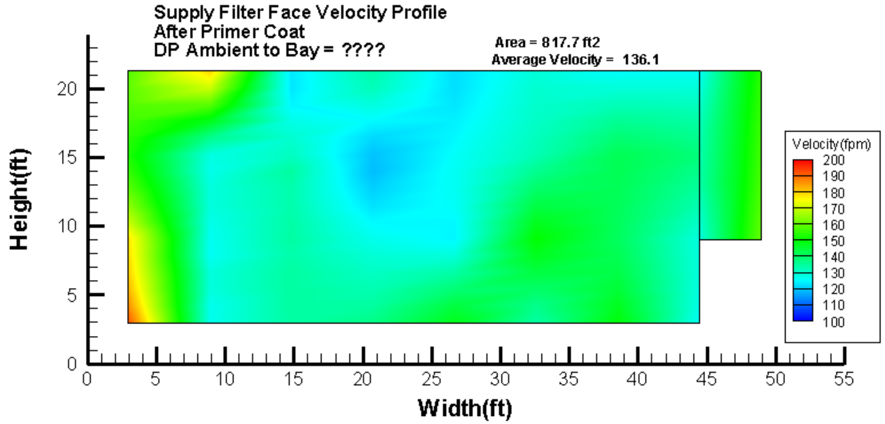



# SUPPLY FILTER FACE VELOCITY PROFILE 02/15/2011

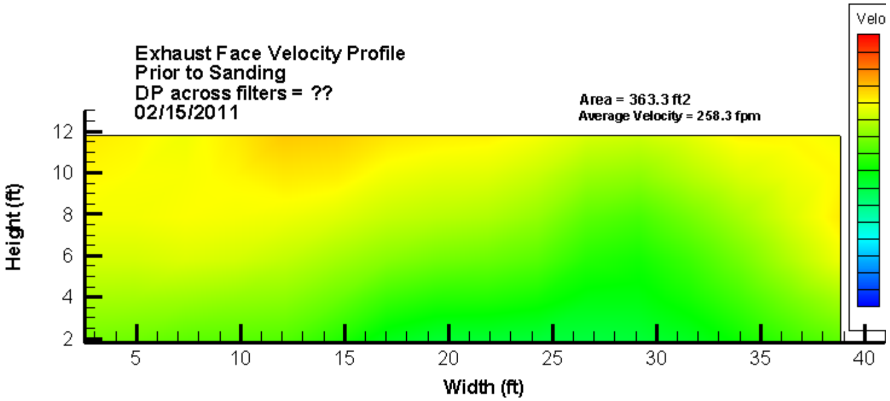


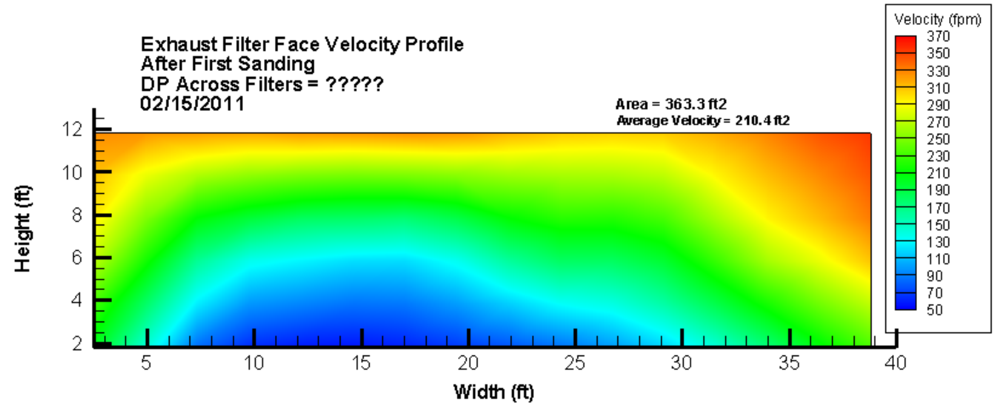



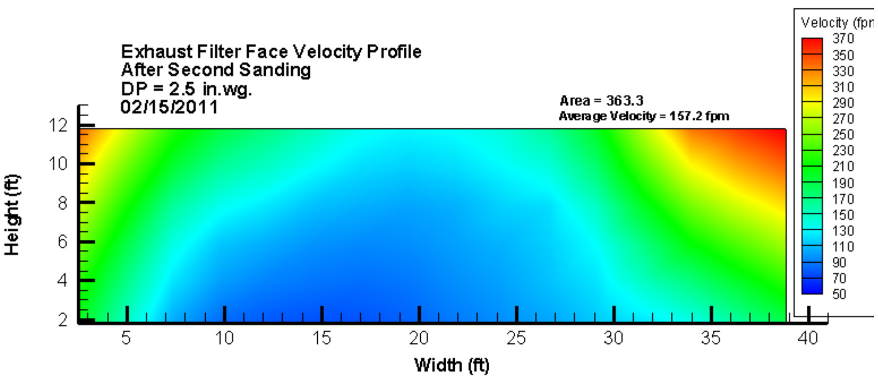
# EXHAUST FILTER FACE VELOCITY PROFILE 02/15/2011

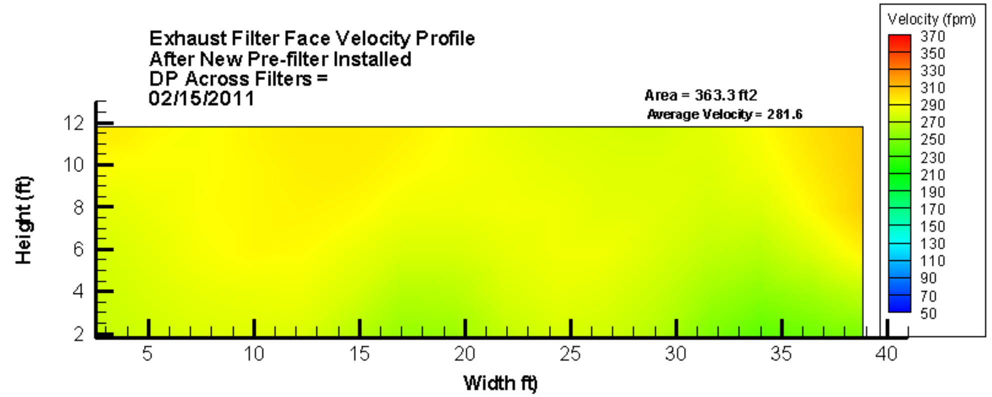



**PARTICULATE AND OVERSPRAY LOADS FILTER**

- *Downwind of higher contaminant areas*
- *Obstructs flow*
- *Creates dead zones upwind*



# Discussion

- **CFD results**
  - 75 fpm is more protective near sources (less turbulent mixing of contaminants)
  - 100 fpm is more protective farther downwind from sources (after mixing) if the flow is obstructed
  - Near-source protection is more important in most situations because exposures are usually higher near sources
  - CFD is a model
  - Balanced flow
- **Tracer gas experiments**
  - Unbalanced flow
  - Supply/exhaust of 103/64 fpm is more protective than 136/99 fpm
  - 73/49 fpm is least protective
- **Overall interpretation**
  - A balanced flow at 75 fpm provides protection similar to a balanced flow at 100 fpm

# Current & Future Efforts

- **Tech Transfer**
  - **NIOSH publish results in technical journals**
  - **NAVFAC ESC completes NESDI report**
  - **Incorporate into UFCs: (1) IV and (2) CC Hangars**

- **NAVFAC ESC seeking ESTCP funding continue modeling verification**
  - **1 larger fixed wing**
  - **2 rotary wing operations**
  - **Other paints**

We're a bargain, we already identified the pitfalls!

# Conclusions

- **Balanced systems are more protective than unbalanced systems**
  - **No rocket science there**
  - **Keeping system maintained is sometimes rocket science or at least it feels that way.**

- **Lesson Learned – Overdesigned or poorly designed supply system can destroy a decent exhaust system**
  - **No rocket science there either**
  - **My mantra – *Look at quantity and distribution*!**

- **CFD and tracer gas analysis indicates that 75 fpm may have similar protection value as 100 fpm**
  - **Remember artisans MUST wear respirators for isocyanates, Cr(VI) and other VOCs exposures, as neither flow rate controls adequately**
  - **Still completing field verification and reporting**

# Project Test Team

- NAVFAC Engineering Service Center
  - Raymond Lucy
  - Kathleen Paulson, PE
- NIOSH
  - James Bennett, PhD
  - David Marlow
  - Duane Hammond, MS, PE
- Southwest Regional Maintenance Center (NASNI, Coronado)
  - James Breay, CIH
  - Carol Lavery, CIH
  - Lydia Ensor – SWRMC Paint Production Manager